

SPACECRAFT MISSIONS AND THE NHMFL

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Asteroids and comets make up the largest number of bodies in our solar system. Although they represent only a small mass fraction of the planetary system, they represent the chemical diversity present in the early solar system. Both asteroids and comets undergo collisions that send debris spiraling in towards the Sun, a fraction of which is encountered by Earth. Chemical and isotopic measurements performed on this material, meteorites and interplanetary dust particles (IDPs), are an important source of information on how our solar system formed (indeed on star and planet formation, in general). These measurements are mainly done by mass spectrometry, a key strength of the facilities at the NHMFL. One limitation to the free gifts of the heaven, meteorites and IDPs, is that their sources are not known. For example, some IDPs are inferred to originate from comets by their morphology and the presence of large isotopic anomalies in D/H ratio, but this is not easy to establish in the absence of bona fide comet samples.

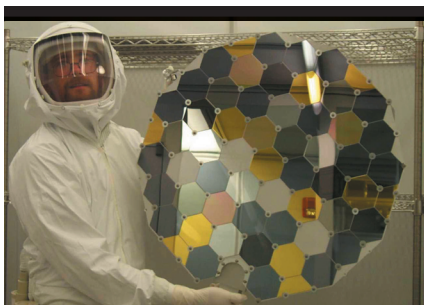
Not since the U.S. Apollo and Soviet Luna missions (1969-1972) have extraterrestrial samples been returned for analysis. That is about to change with three sample return missions underway. The GENESIS mission collected solar wind ions implanted in high-purity substrates, and returned to Earth September 2004. The STARDUST mission collected cometary dust from Comet Wild2, which will be returned to Earth, January 2006. The Japanese HYABUSA Mission will collect and return samples from Asteroid Itokawa in 2007. The quality of analysis that can be performed in ground-based laboratories is many orders of magnitude better than measurements that can be performed by spacecraft-borne instrumentation. Spacecraft instruments are restricted in their capabilities by payload requirements, i.e. instruments must be small and limited in their power requirements. Ground-based laboratories can analyze radioisotope ages of rocks and soils that cannot be performed by remote instruments. Sample return from bodies lacking large gravitational fields is technically feasible and places comets and asteroids within reach.

The principal challenge facing ground-based laboratories that have worked with rock and soil samples from Earth, Moon, and meteorites is that the amount of material returned by the three spacecraft missions is significantly smaller than previous endeavors. The Apollo missions returned nearly 400 kilograms of rock and soil from the Moon. By comparison, STARDUST collected about 1,000 particles 15 to 100 microns in diameter. Evidently



microanalytical methods will need to be used to get the most information from these tiny samples. Among the techniques available to the space science community are scanning electron microscopy (SEM), transmission electron microscopy (TEM), secondary ion mass spectrometry (SIMS), and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS).

Each technique provides a different type of information. Electron microscopy provides chemical composition of major elements and morphology; SIMS provides elemental and isotopic analyses of low FIP (First Ionization Potential, $FIP < 7$ eV) elements; LA-ICP-MS analyzes elements of $FIP < 12$, but occupies a unique niche for elements with $FIP \sim 7-12$. Laser ablation ICP-MS is a new tool at the NHMFL Geochemistry labs, however, the technique is presently limited to >10 μm scale, providing only bulk analysis of the largest cometary grains. This is due to a low duty cycle for magnetic sector mass spectrometers due to magnetic hysteresis. It is this aspect



Leading page: an artist's conception of the STARDUST spacecraft. **On Left:** a GENESIS Mission collector array prior to flight. Eight different collector materials are represented among the hexagons, including Si wafers (dark gray) and Si-on-sapphire wafers (yellow). Images courtesy of NASA.

of laser ablation microanalysis that new initiatives at the NHMFL Geochemistry program seek to advance.

In laser ablation, a burst of UV laser light (266 nm, 213 nm or 193 nm) is focused on the specimen. This produces a pulse of aerosol from the ablated specimen that is swept by a continuous stream of argon (Ar) gas into an Ar plasma where it is ionized. The innovation we are developing is to split the aerosol and then send it to two mass spectrometers (MS), simultaneously. Nature has provided us with the convenience that low mass elements are generally much more abundant in the cosmos than high mass elements. Thus, one MS scans the abundant peaks in the low mass range (e.g., ^7Li to ^{60}Ni), while the other, a multicollector ICP-MS equipped with multi-ion counters, statically collects a single portion of the high mass range. By carefully choosing the elements of interest, the Dual-MS technique increases the information return on small grains by nearly 40-fold. One mass range of interest is that of Hf-Pb. For nuclei heavier than ^{56}Fe , two nucleosynthetic processes manufacture most of the isotopes: slow neutron capture (s-process) which takes place in red giant stars, and rapid neutron capture (r-process) which takes place in supernovae. The solar system has a unique and relatively homogeneous mixture of the two. In the Hf-Pb mass range of the solar mix some elements are produced dominantly by the s-process (Pb), others by the r-process

(e.g., Pt, Au). Interstellar grains need not have the solar s/r mixture, and comets are believed to have preserved many interstellar grains in their ices.

Dual-MS detection results in a very significant improvement in the detection limits of high-mass elements over single-MS detection, so that lasers with spatial resolution of 4 microns can be used for elemental analysis. At 4 μm spatial resolution, a cometary grain of 15 microns or larger can now be analyzed in different parts to determine compositional variability in the grain. Such variability is expected on the basis of recent studies of "cometary IDPs." The IDPs (interplanetary dust particles) are cosmic dust grains originating from asteroids, and possibly comets, that fall to Earth and are collected by NASA U-2 aircraft from the stratosphere. These particles include some so small they are slowed to terminal velocity in the atmosphere before heating up significantly enough to melt, preserving delicate structures. Some are interpreted to be cometary dust. One of these particles is the GEMS (Glass with Embedded Metal and Sulfides). The individual Fe-metal and FeS grains are interpreted to be stellar condensates and are nano-metre scale particles embedded in a silicate glass. Analysis of individual nm-size grains is not feasible, but analysis of clumps of Fe-metal within Fe-bearing silicates will enable identification of distinct stellar chemical or isotopic signatures to be resolved.

Another mystery observed in "cometary" IDPs is the presence of optically clear silicate mineral grains (particularly, enstatite MgSiO_3). Grains that have resided in the interstellar medium accumulate UV irradiation damage, so these grains were either radially transported from the inner solar system or were introduced into the interstellar medium shortly before incorporation into the solar system by a nearby star. Such a star may also introduce the "extinct" radionuclides observed in meteorites.

New developments in microanalysis and inorganic mass spectrometry at the NHMFL contribute to solution to these mysteries. In the process, we will develop a deeper understanding of the formation of asteroids and comets, unprecedented by previous work on IDPs. A thousand grains of authentic cometary material will undoubtedly reveal new insights into the events surrounding the birth of our solar system.

Notes:

The sample container of the GENESIS Mission was released and re-entered the Earth's atmosphere. It was intended that parachutes would deploy, and the sample capsule then captured in mid-air by helicopters. The parachutes failed to deploy and the capsule struck the ground at about 200 mph, shattering many of the collectors. Despite that, fragments of the high-purity substrates will soon be made available for distribution to the space science community.

The STARDUST mission is due to return interstellar and cometary dust samples to Earth by January 2006. The spacecraft encountered the dust tail of Comet Wild2 and dust particles from the tail were collected in aerogel (silica foam) collectors. The encounter velocity was low enough that the particles would have experienced minimum impact heating, preserving intact grains for analysis.